A Deep learning method for real-time intraoperative US image segmentation in prostate brachytherapy

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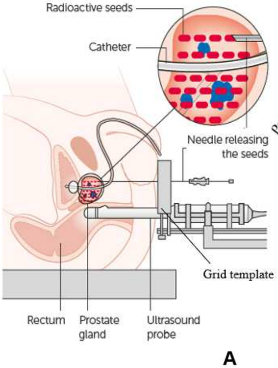
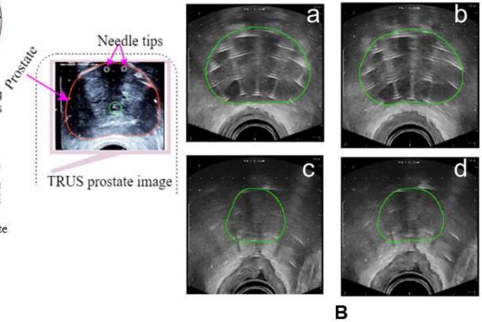
Prostate brachytherapy

A typical intra-operative procedure in permanent brachytherapy





A. Schematic representation

B. Prostate TRUS images

Prostate clinical target volume segmentation

Objective

- To develop a robust and automatic method for prostate gland segmentation in intra-operative TRUS images

Challenges

- Large variations of prostate size and shape
- Low-contrast at the edge of the prostate gland
- Inherent high artifacts of ultrasound imaging
- Strong artifact signals from the needle and the implanted seeds

Hypothesis

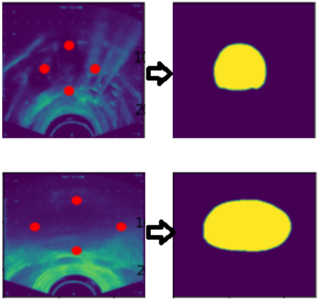
Learning-based shape reconstruction from automatically sampled prostate boundary coordinates along with the deep learning-based pixel classification (e.g., U-net) can automatically detect the low-contrast and noisy region of the prostate in TRUS images.

Dataset

- Transrectal ultrasound (TRUS) images
  - 145 TRUS exams
  - Permanent prostate brachytherapy with ^{125}I
  - Plane resolution of 0.1038 x 0.1038
  - The series of transverse 2D TRUS images were acquired at 1 mm intervals

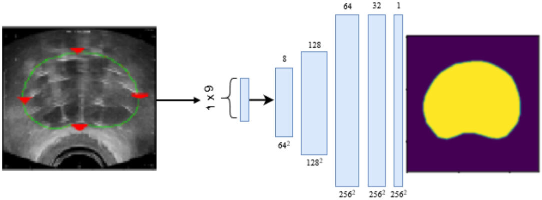
Pre-processing

- Resized to $0.25 \times 0.25 \times 1\ mm^3$
- Center cropped to an image resolution of $256 \times 256 \times 64$
- Extracted four extreme coordinate points of the prostate from the ground truth for the training

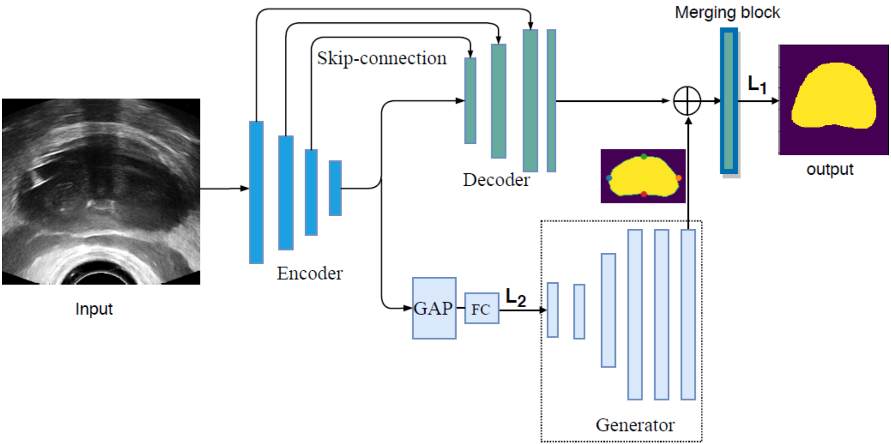


Input Ground truth

Mask generator



- Binary cross-entropy loss function
- Regression for surface coordinates x and y
- Image based classification from z direction



Proposed end-to-end architecture

Loss function

$$L = \gamma L_1 + (1-\gamma) L_2, \tag{1}$$

where L_1 is the segmentation cost function (i.e., $L_1 = L_{dice} + L_{bce}$) and L_2 is the classification and regression cost function.

$$L_2(I^u, I^v) = L_{cls}(p, s^u) + \lambda \times s^u \left(1 - Regression\right), \tag{2}$$

$$Regression = \left(\frac{1}{1 + \sum_{i \in \{x,y,s=1\}} smooth_{L1}(t_i^u - t_i^v)} \right), \tag{3}$$

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Ablation study

Metric	U-net	U-net + Se	U-net + Se + Gn
DSC	0.79 ± 0.04	0.87 ± 0.02	$\mathbf{0.88} \pm \mathbf{0.03}$
HD95	4.05 ± 0.63	2.38 ± 0.58	$\mathbf{2.01} \pm \mathbf{0.54}$

U-net: Convolution + activation + Batch normalization
U-net + Se: U-net + squeeze-and-excitation network[1]
U-net + Se + Gn: U-net + Se + generator
DSC: Dice Similarity Coefficient
HD95: 95% Hausdorff distance (in mm)

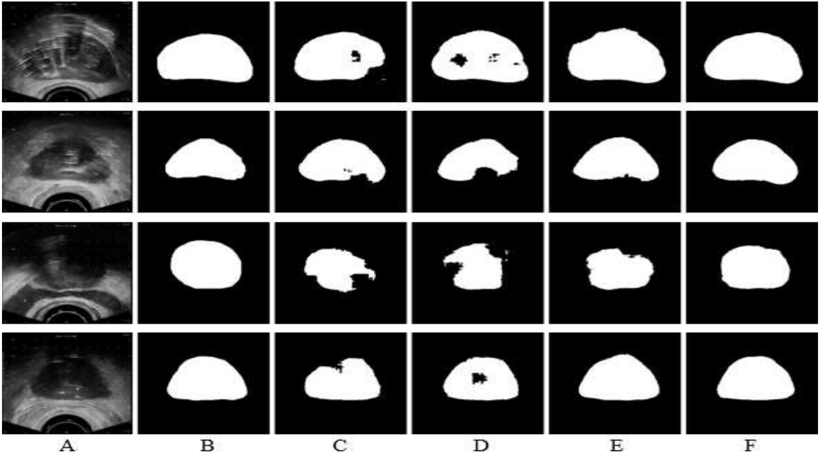
[1] Hu J, et al. Squeeze-and-excitation networks. CVPR, 2018

Comparison of experimental results

Metrics	U-net	Res-Unet	Res-Se-Unet	**Proposed**
DSC	0.79 ± 0.04	0.78 ± 0.04	0.86 ± 0.03	$\mathbf{0.88} \pm \mathbf{0.02}$
HD95	4.05 ± 0.63	4.40 ± 0.74	3.17 ± 1.45	$\mathbf{2.01} \pm \mathbf{0.54}$
HD	16.0 ± 7.60	15.2 ± 6.27	14.79 ± 5.98	$\mathbf{8.37} \pm \mathbf{2.93}$
Sn	0.79 ± 0.07	0.80 ± 0.07	$\mathbf{0.92} \pm \mathbf{0.03}$	0.88 ± 0.05
Sp	0.96 ± 0.01	0.96 ± 0.02	0.96 ± 0.02	$\mathbf{0.98} \pm \mathbf{0.01}$
Acc	0.93 ± 0.02	0.93 ± 0.02	0.95 ± 0.95	$\mathbf{0.96} \pm \mathbf{0.01}$
Asd	0.33 ± 0.18	0.41 ± 0.21	0.33 ± 0.11	$\mathbf{0.10} \pm \mathbf{0.06}$

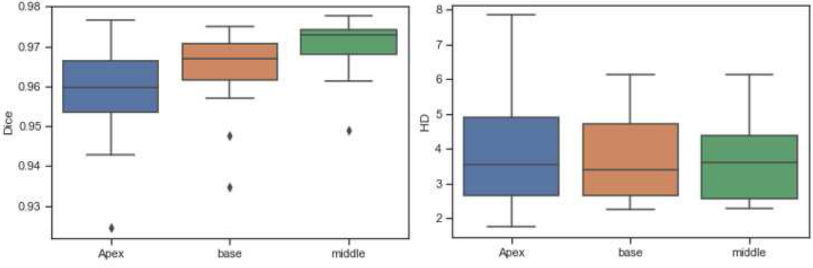
Sn: sensitivity
Sp: Specificity
Asd: Average surface distance

Qualitative results



(A) Input image, (B) Ground truth labels, (C) U-net, (D) Res-Unet, (E) Res-Se-Unet and (F) proposed method

Mask generator results



(a) (b)

- Average Dice similarity coefficient of 0.97
- Average Hausdorff distance error of 4.11 mm

Summary and remarks

Take home message

- Embedding prior organ knowledge via learning-based shape modeling and registration can improve image segmentation
- The prostate shape can be generated from a few sampled boundary coordinates
- Channel-wise feature calibration network enhances the performance of deep learning method

Future work

- Use the spatial-temporal information between adjacent slices
- Train the generator from MRI images

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